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Cyclic NO and NO_2 formation in a compression ignition engine

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Contents

Background

- NO_x known to affect human health
- Control of NO_x essential on all diesel engines
  - Engine approaches – e.g. EGR
  - Aftertreatment – e.g. SCR
- Here: $NO_x = NO + NO_2$
  - Amount of each can vary
- SCR ➔ ~50/50 NO / NO_2
- NO_2 promotes DPF regen

Background

- NO_x formation by extended Zeldovich mechanisms:

  $O + N_2 \rightarrow NO + N$
  $N + O_2 \rightarrow NO + O$
  $N + OH \rightarrow NO + H$

- T > 1000 K: $NO \rightarrow NO_2$

  $NO + HO_2 \rightarrow NO_2 + OH$

- T > 1500 K: $NO_2 \rightarrow NO$

  $NO_2 + O \rightarrow NO + O_2$

- Hence composition “freeze” at EVO
- Engine parameters will have an effect on NO_2/NO_x ratio

Background

- NO_2 5-30% of total NO_x (engine-out)
- NO_2/NO_x ratio important e.g. for SCR efficiency & DPF regen
- Typical effects of engine parameters on NO_2/NO_x ratio:

Parameter increasing	NO_x emission	NO_2/NO_x ratio
λ	↑	↑
SOI	↓	↑
Fuel pressure	↓	↑
EGR rate	↓	↑
Charge temperature	↓	↑
Humidity	↓	↑

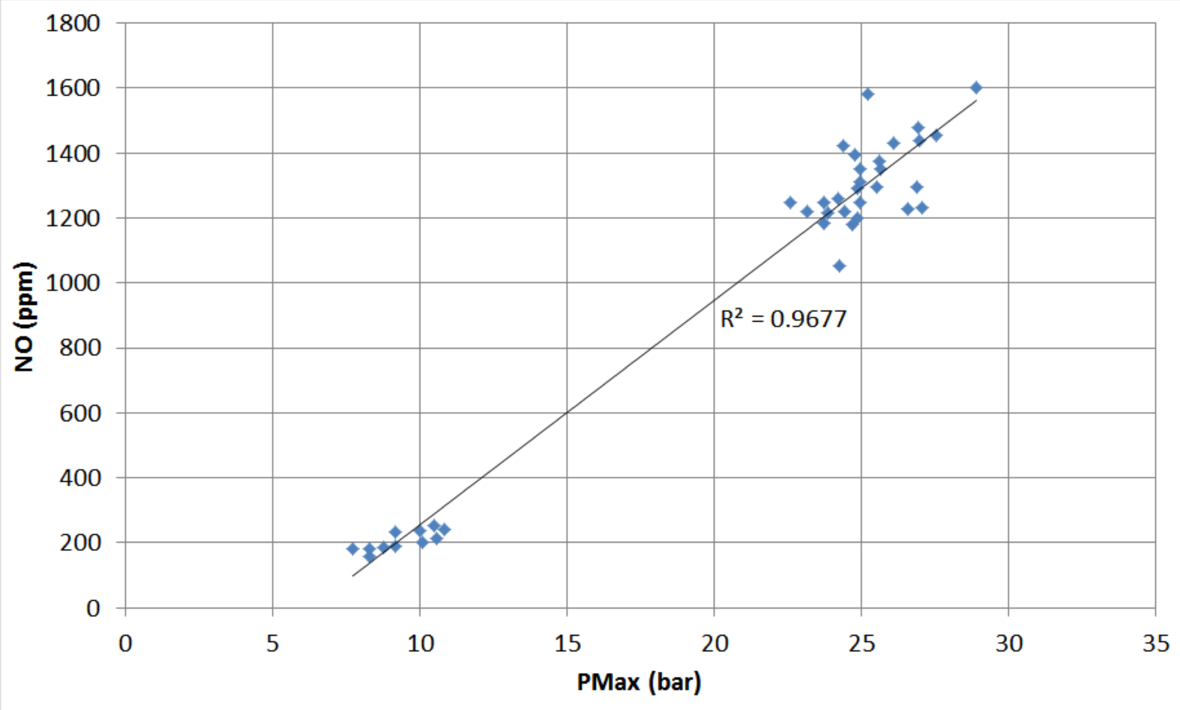
Rößler, M., et al., *Formation of Engine Internal NO2: Measures to Control the NO2/NOX Ratio for Enhanced Exhaust After Treatment.* SAE International Journal of Engines, 2017. **10**(4): p. 1880-1893

Aim

- High speed measurement of NO and NO_x
- Investigate NO and NO_x variations with engine conditions
  - Hence NO_2/NO_x ratio
- Understand effect in-cylinder conditions have on NO and NO_x
- Investigate cycle-to-cycle variations

Background

- NO formation dependence on temp
- Gasoline link between cyclic NO and P_{Max}
  - P_{Max} and T_{Max} closely correlated



Ball, J.K., et al., *Validation of a Cyclic NO Formation Model with Fast NO Measurements*. SAE Technical Paper 2001-01-1010

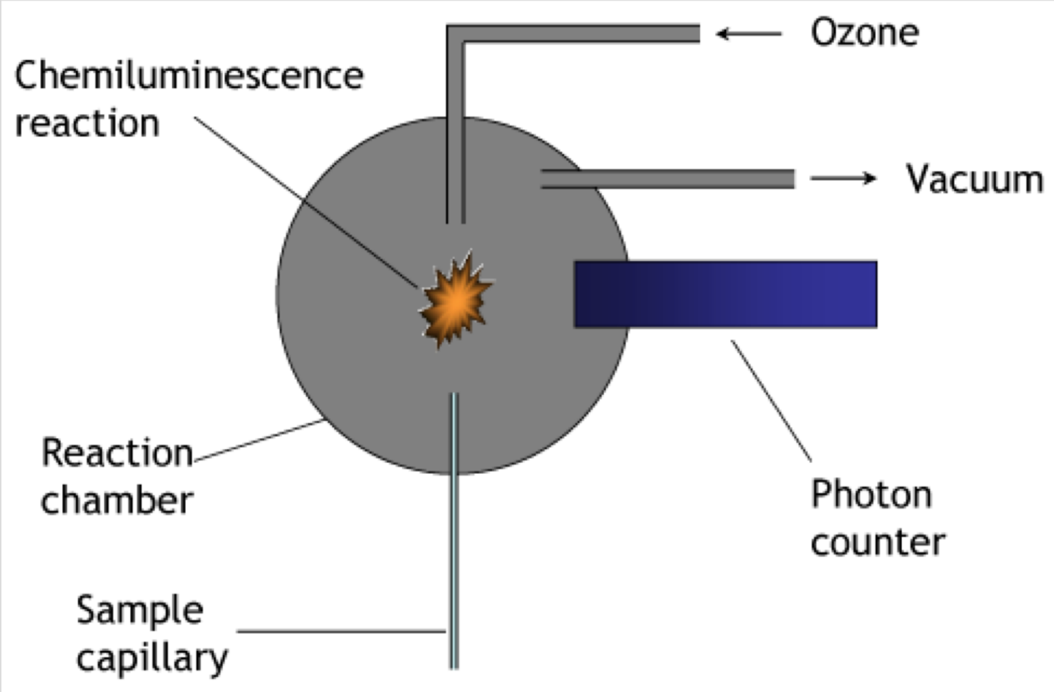
Experimental equipment

- Ricardo Hydra Single Cylinder Diesel Engine
- External boosting rig & conditioning systems
- Cylinder pressure with Kistler 6046
- Horiba MEXA-ONE

Displacement / cylinder	**500 cm^3**
Valves per Cylinder	**2 intake, 2 exhaust**
EVO	**128 °atdcf**
EVC	**382 °atdcf**
Fuel Pressure	**2200 bar maximum**

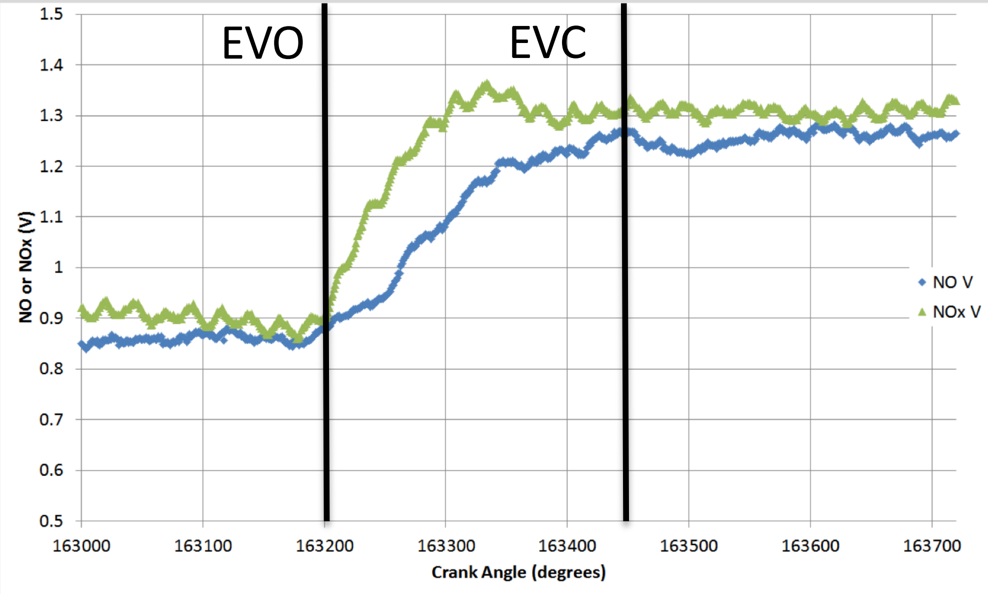
Experimental equipment

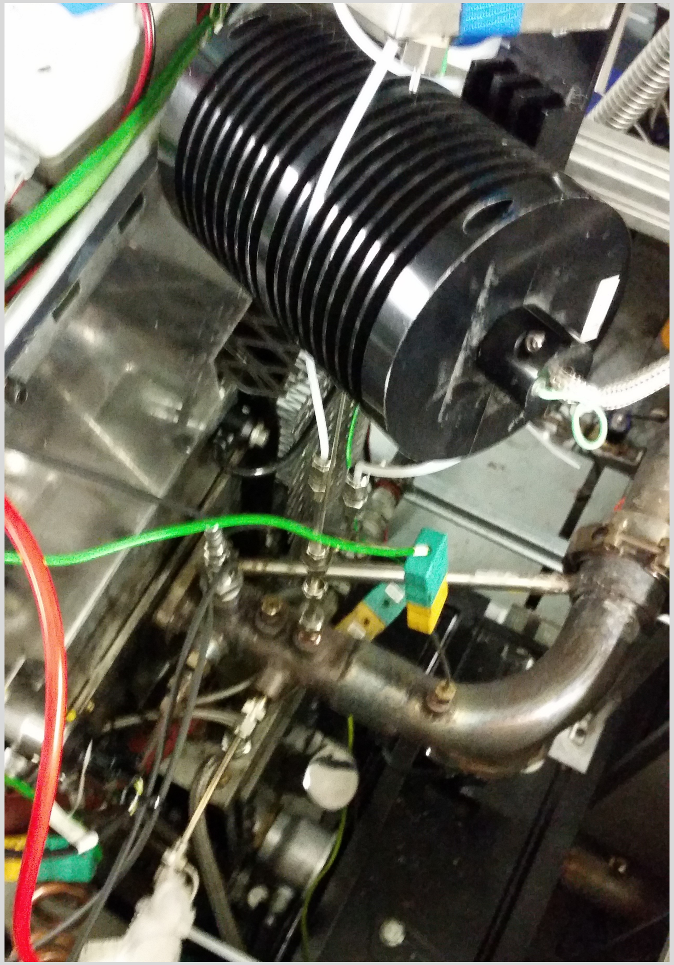
- Cambustion CLD500 Fast NO/NO_x sampling
- Two channels – NO & NO_x
- NO: 2 ms $T_{10\text{-}90\%}$ NO_x: 10 ms $T_{10\text{-}90\%}$



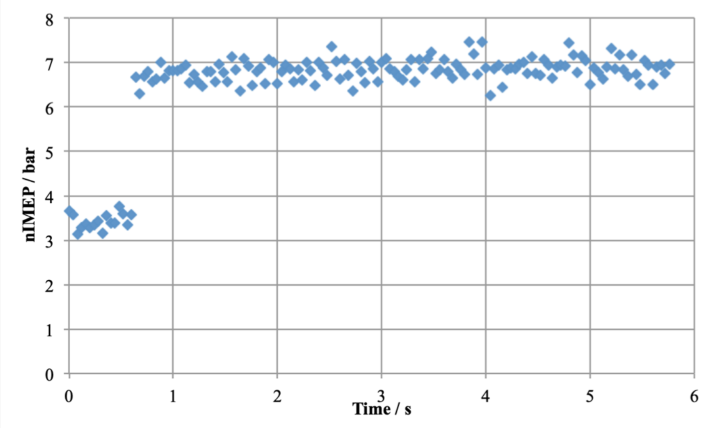
Experimental equipment

- NO & NO_x sensors 70 mm downstream of exhaust port
- 0.1 CAD logging by AVL IndiSet
- Signals time aligned





Methodology



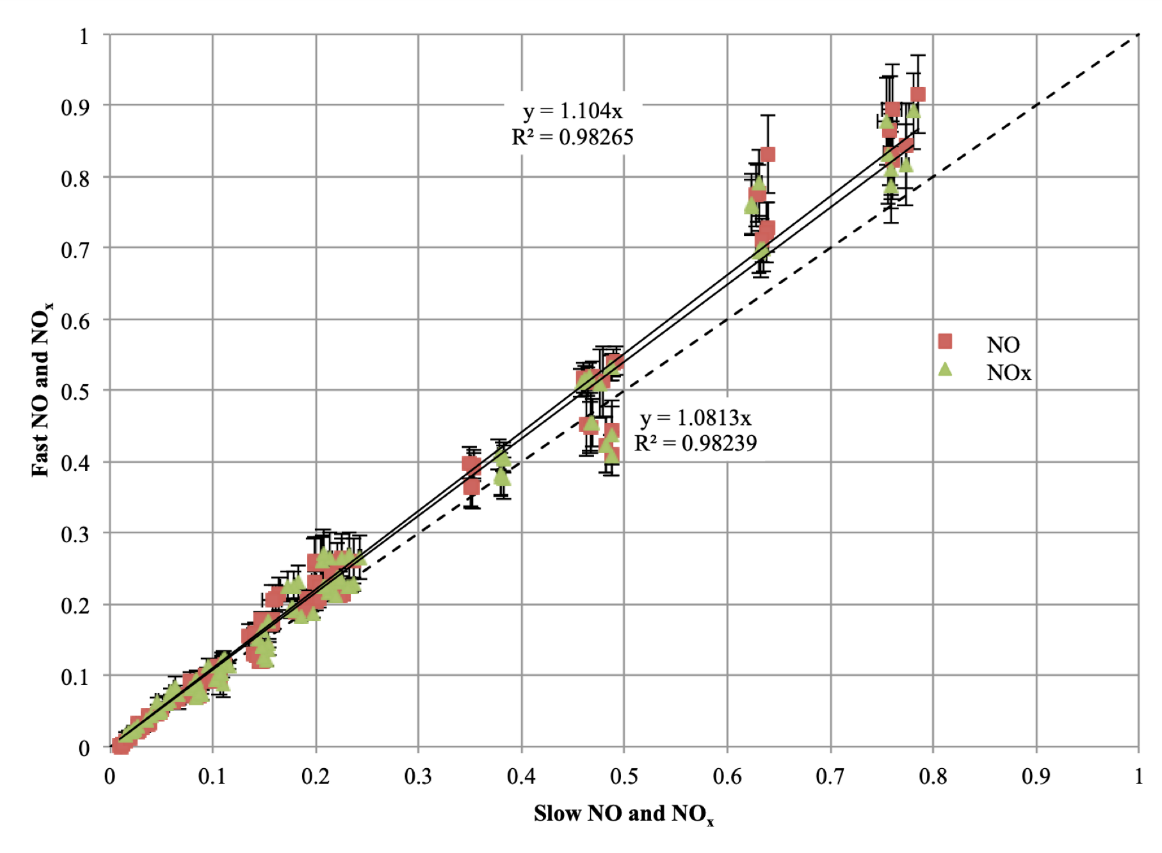
- 4x load/speed points
- 2x EGR levels at each point
- Engine load stepped at constant speed

Test point	1	2	3	4	5
Engine speed (rpm)	1500	1500	2000	2000	2500
nIMEP (bar)*	3.8	6.9	12.3	25.8	17.7
Exhaust back pressure (barG)	0.31	0.84	2.0	2.9	2.7
Inlet air temperature (°C)	55	40	40	40	40
Coolant and oil temperature (°C)	90	90	90	90	90
EGR (%)	0 & 45	0 & 32	0 & 22	0	0 & 15

*Target nIMEP for the point, the engine load was stepped between half of this value and the target, except TP4 (three-quarters).

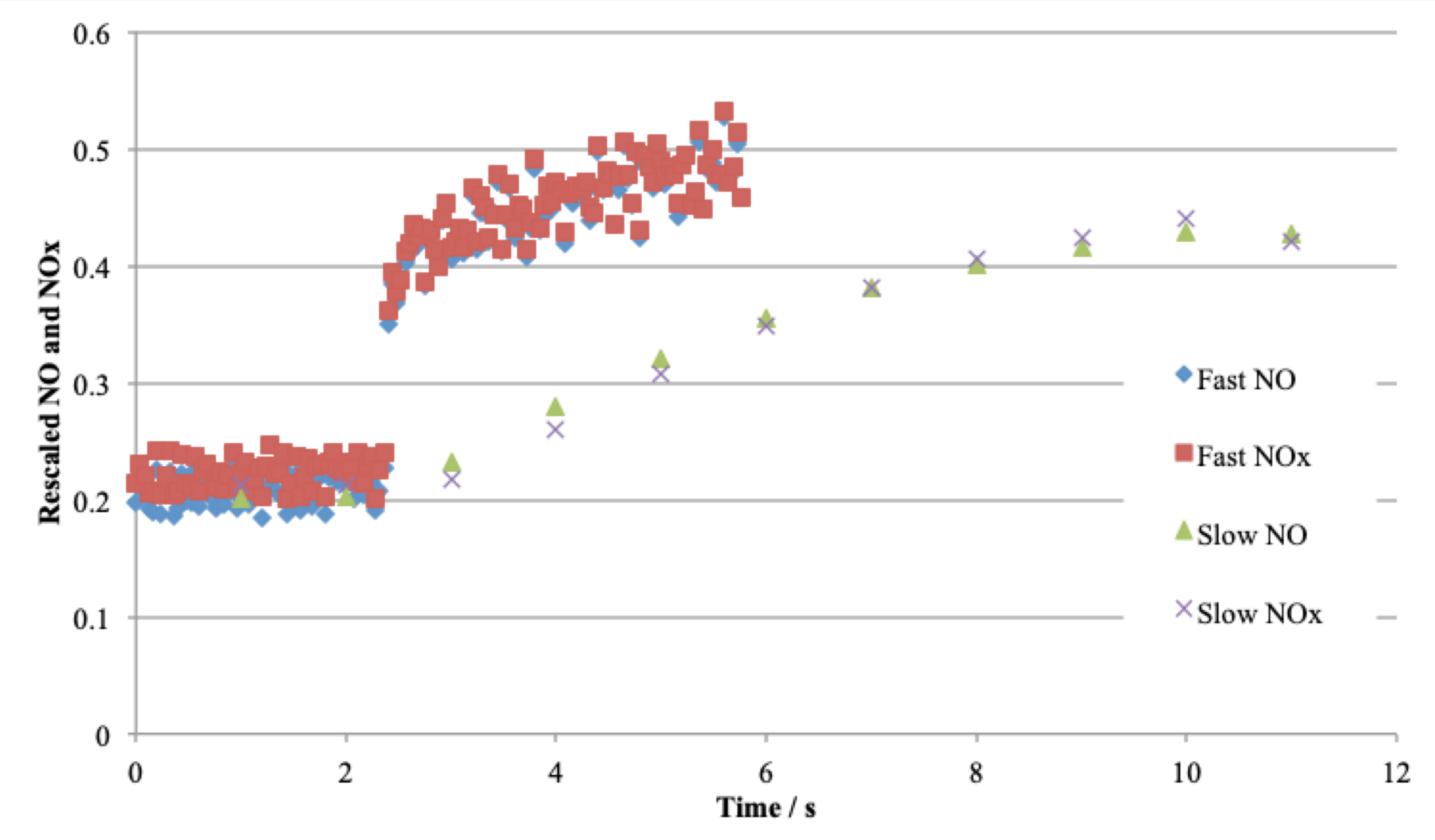
Results – comparison between analysers

- Close agreement between Cambustion CLD500 and Horiba MEXA



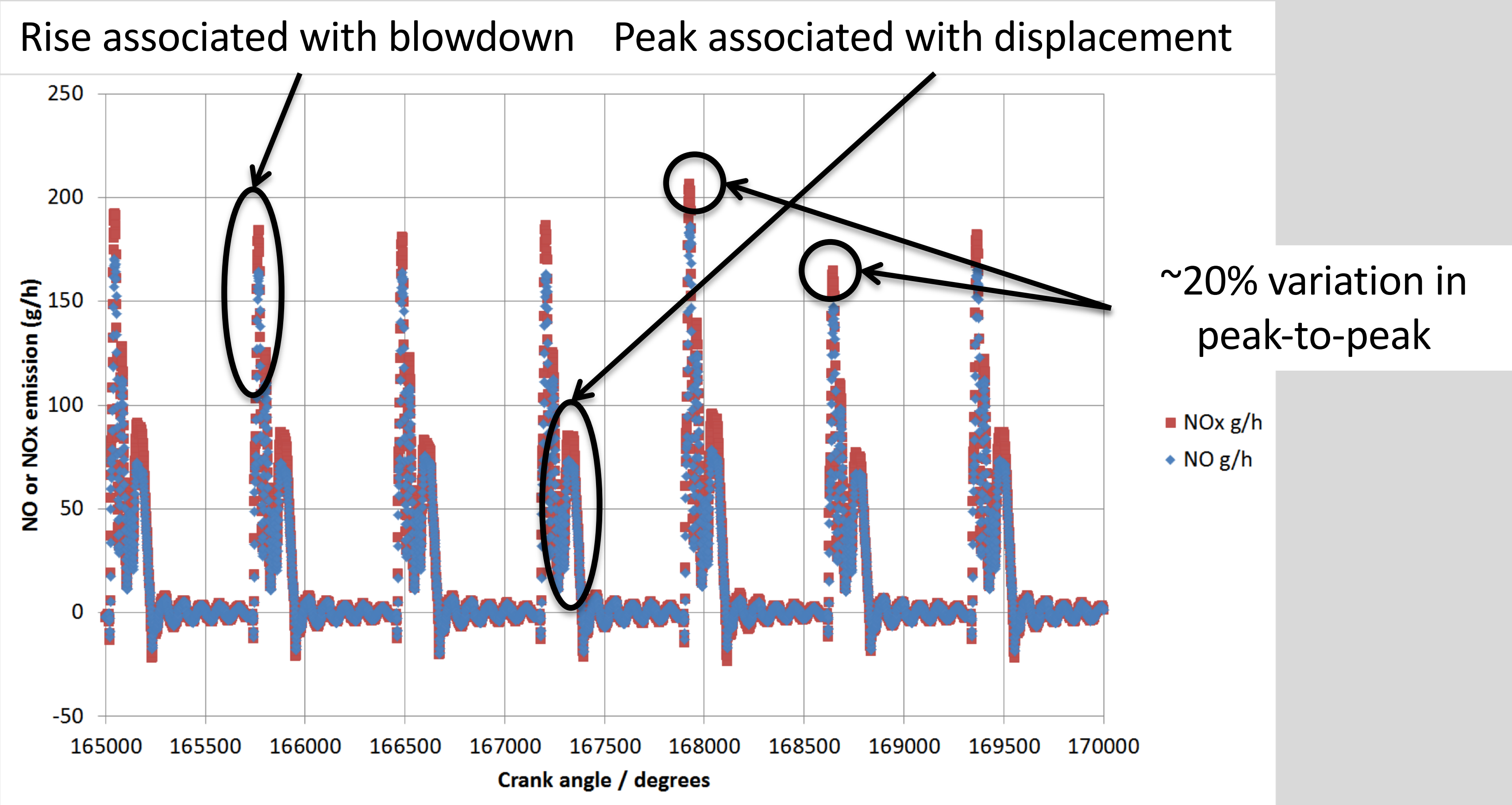
Results – comparison between analysers

- CLD500 response captures transient change instantaneously



Results

- 7 cycles at TP2 (1500 rpm, 6.9 bar nIMEP)



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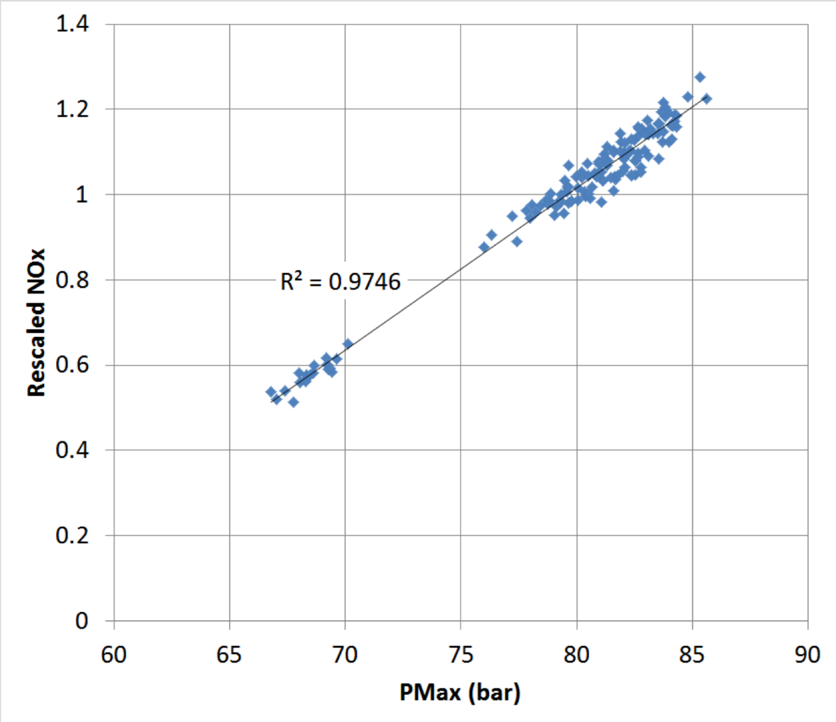
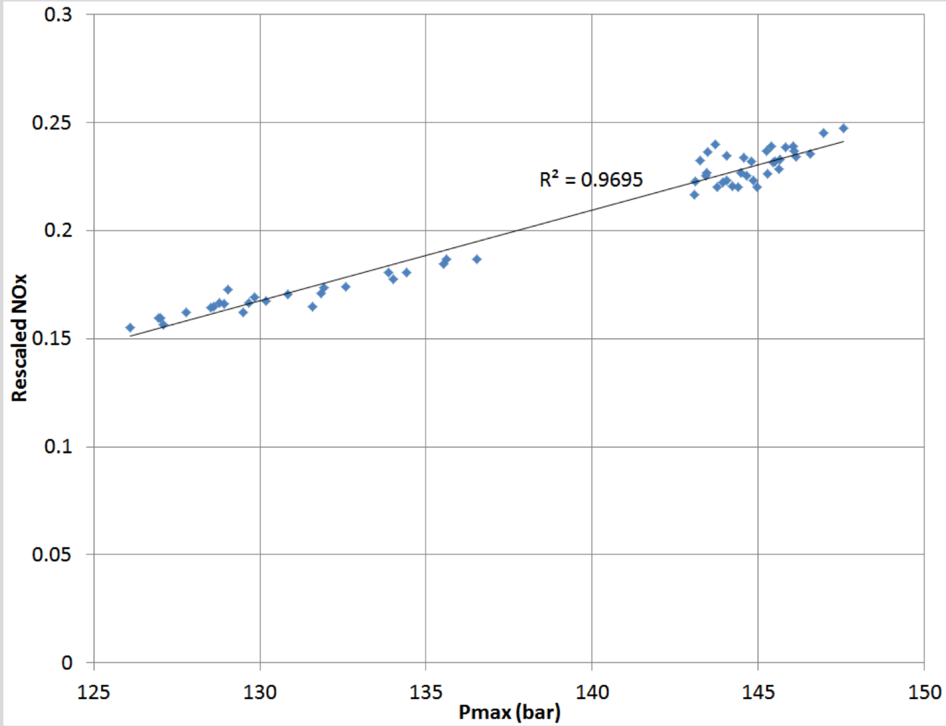
Results – cycle resolved

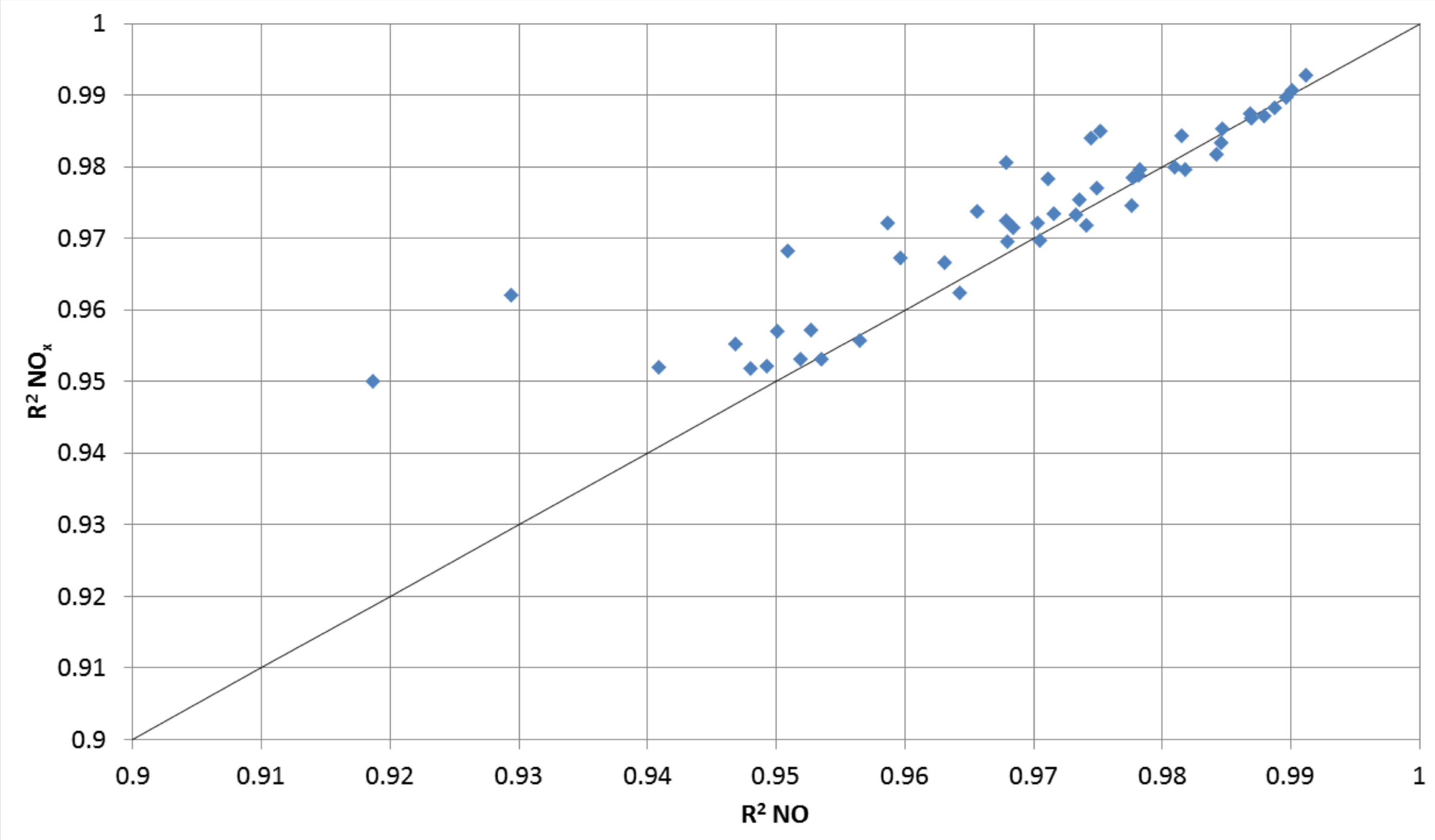
- Correlation between P_{Max} and NO_x at TP2 (1500 rpm, 6.9 bar nIMEP, 0 EGR) & TP4 (2500 rpm, 17.7 bar nIMEP, 15% EGR) – each point = 1 cycle
- Different correlations (different NO_x levels) but strong





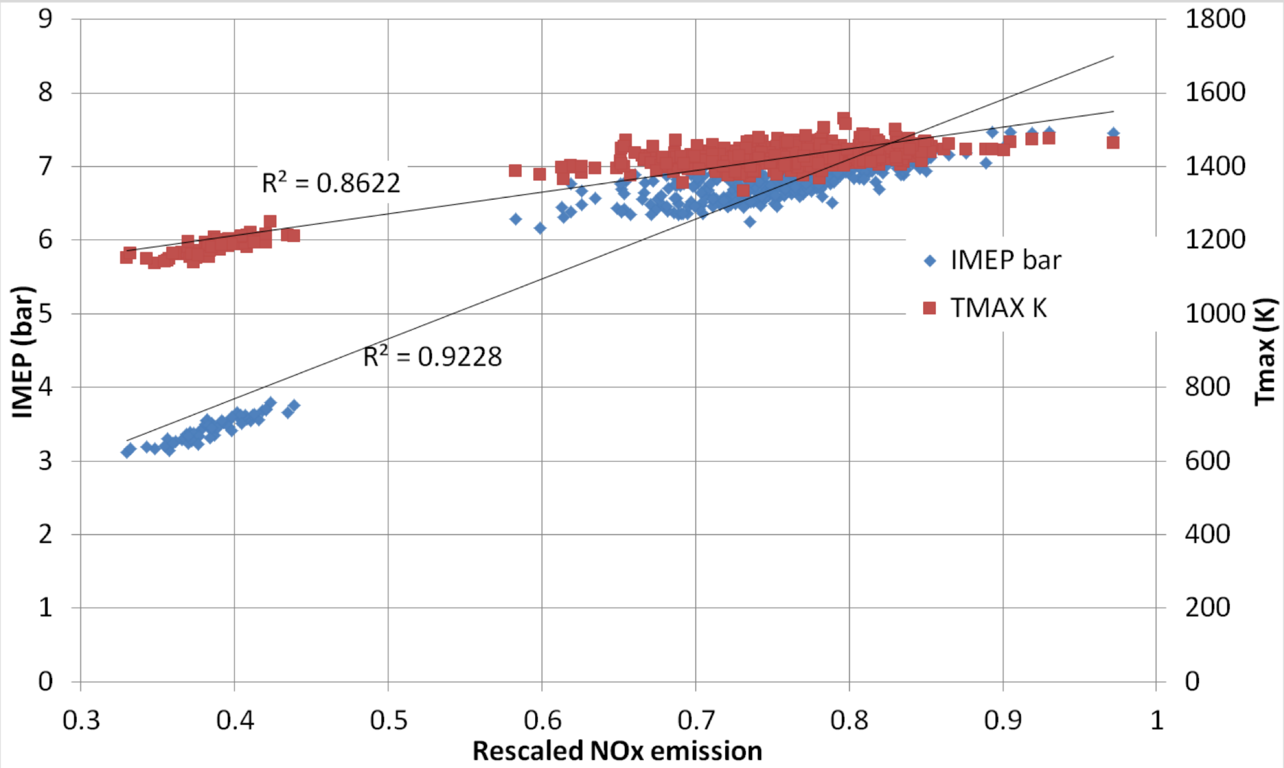
Results – cycle resolved

- Correlation always >0.95 for NO_x, >0.91 for NO
- Stronger for NO_x as NO_2 ➔ NO conversion happens



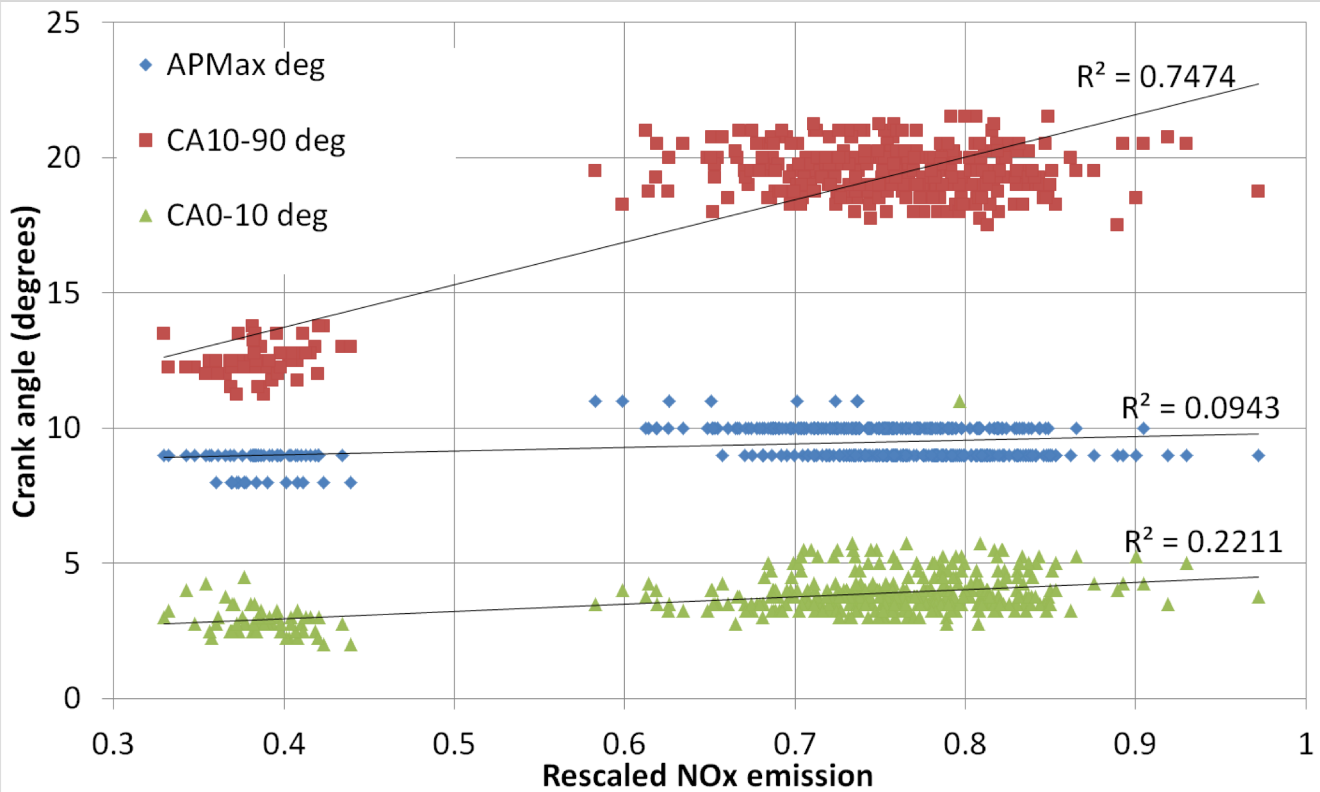
Results – cycle resolved

- Do other combustion parameters have as strong an effect on NO_x?
- Both T_{Max} and IMEP derived from pressure ➔ error propagation ➔ weaker correlation



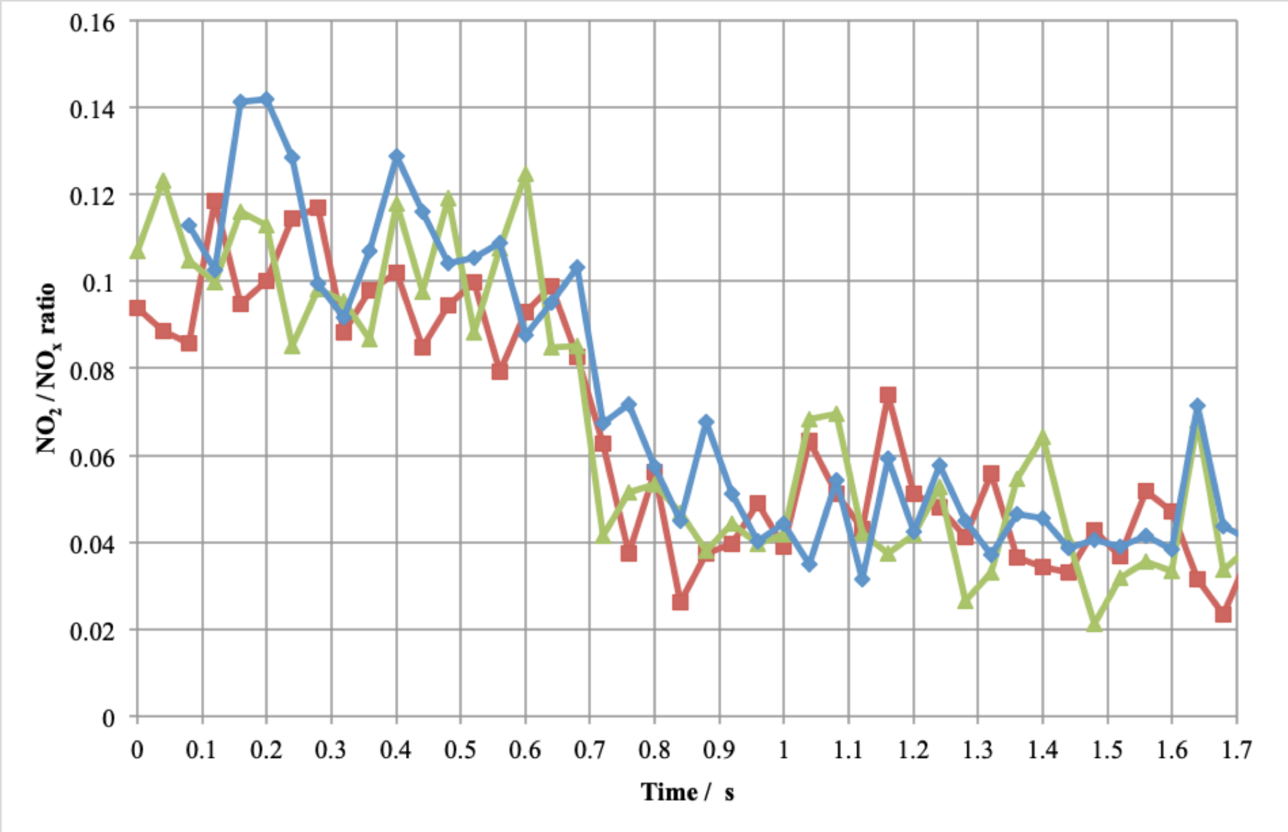
Results – cycle resolved

- Other combustion parameters show very weak / flat correlation



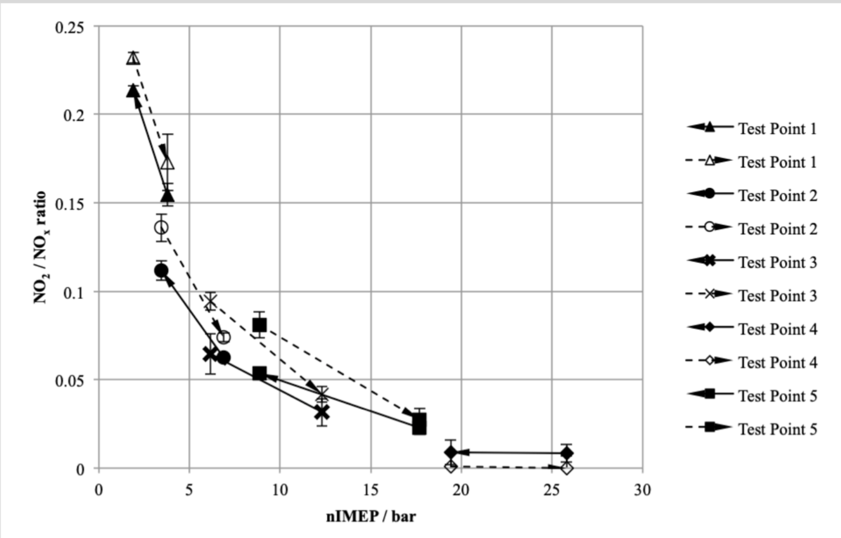
Results – cycle resolved

- NO_2/NO_x ratio response is instantaneous with load step

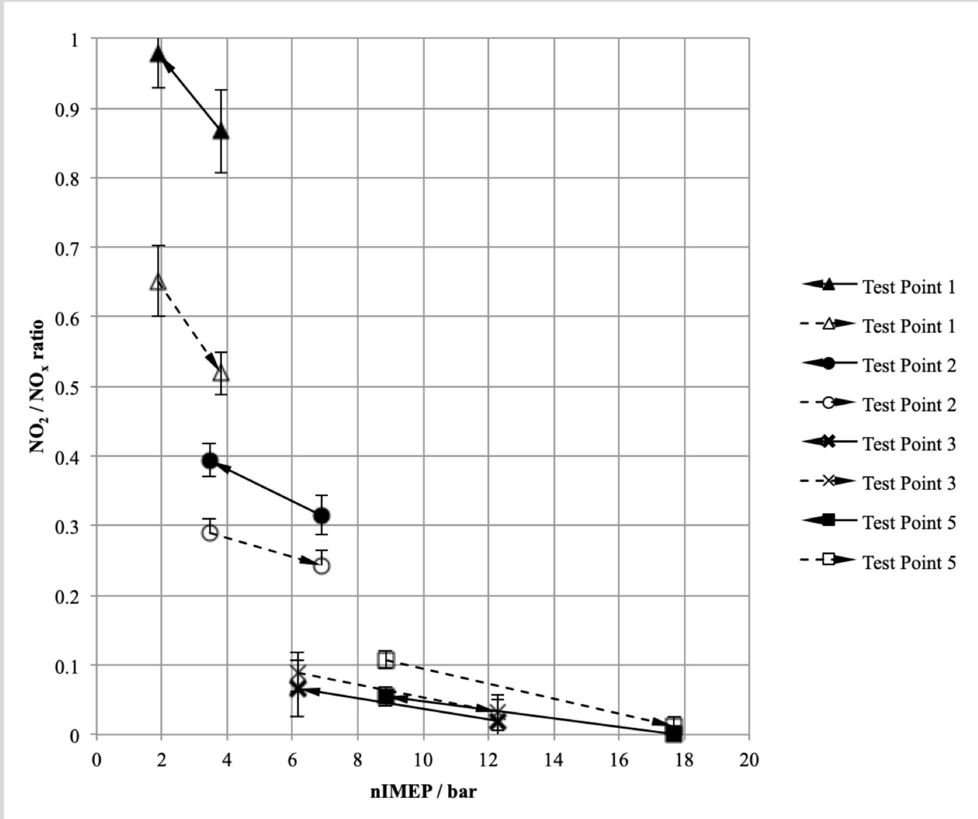


Results – cycle resolved

- Instantaneous changes in NO_2/NO_x ratio in line with literature
- w/EGR some v high values observed (but low NO_x)



No EGR

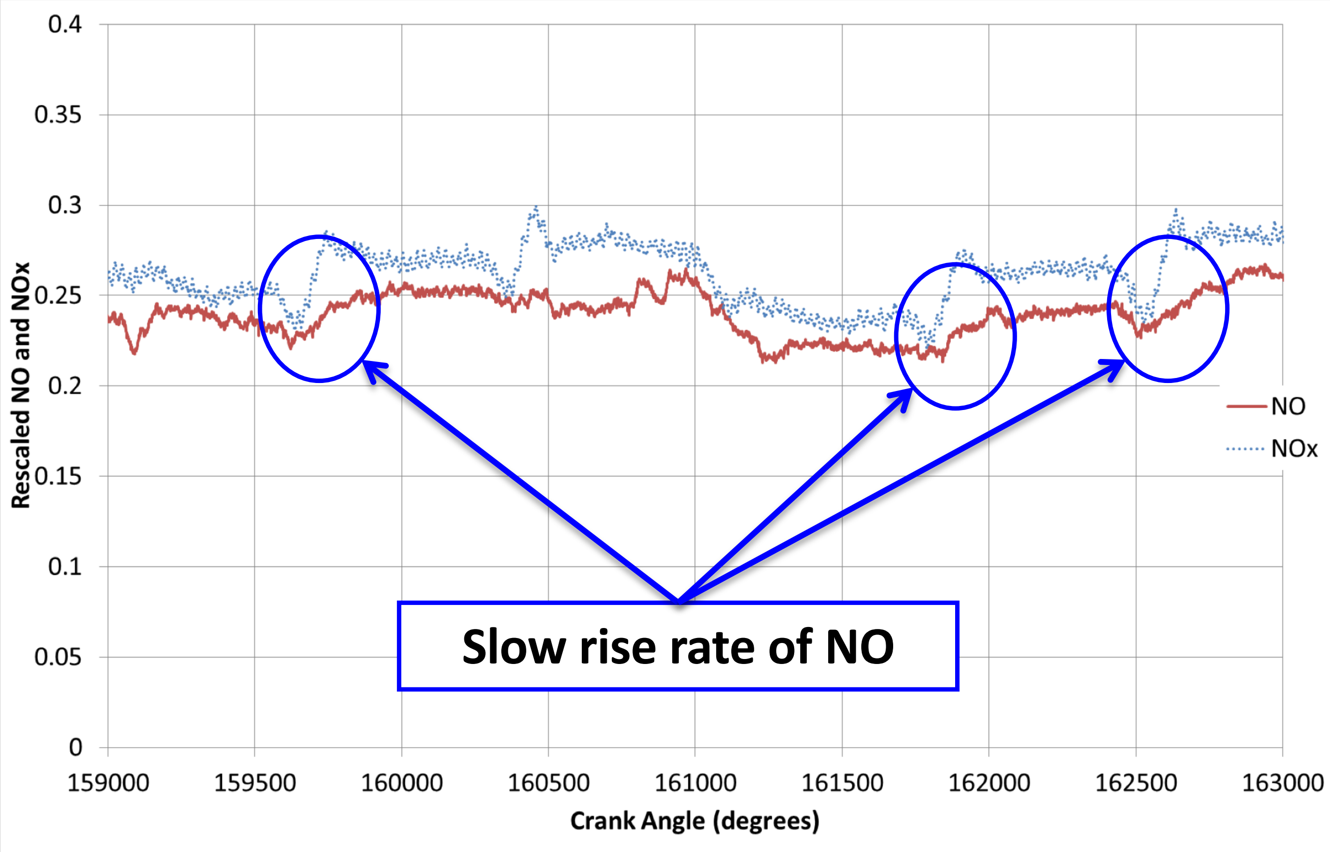


With EGR

Results – crank angle resolved

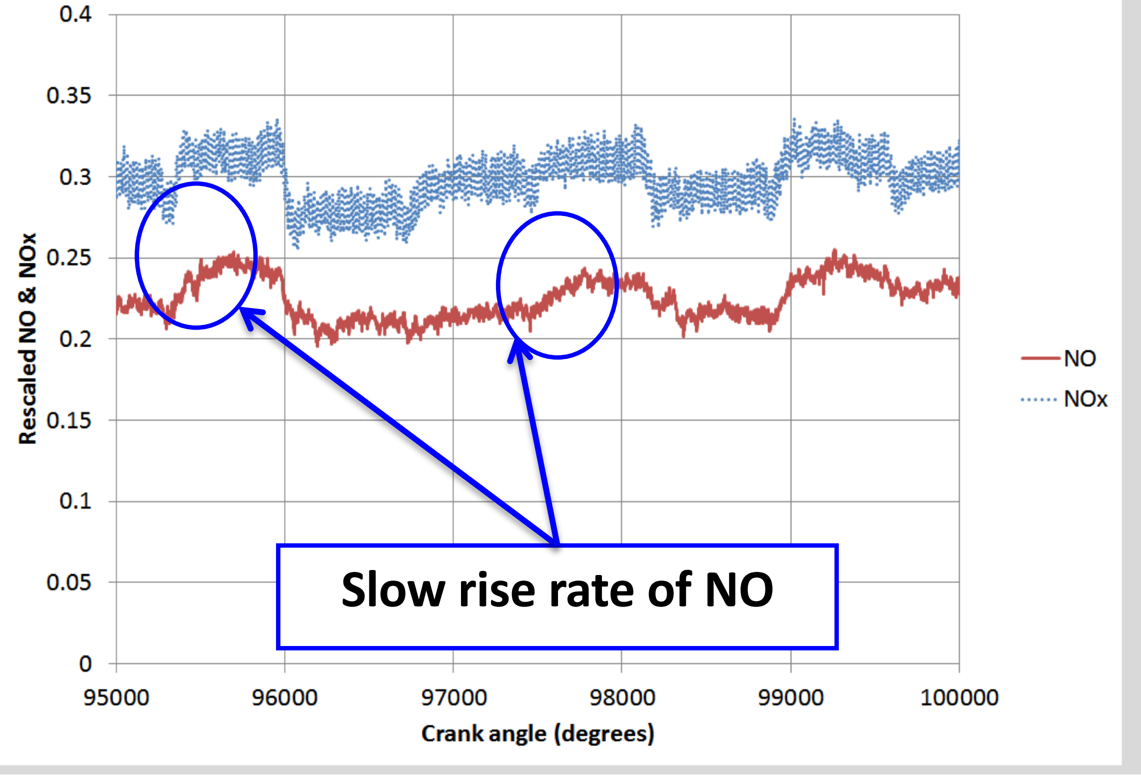
- Crank angle resolved data reveals slow rise of NO – but not every cycle (2000 rpm / 12.3 bar, 0 EGR)

- Occurs ~50% of cycles when NOx rises c.f. previous cycle



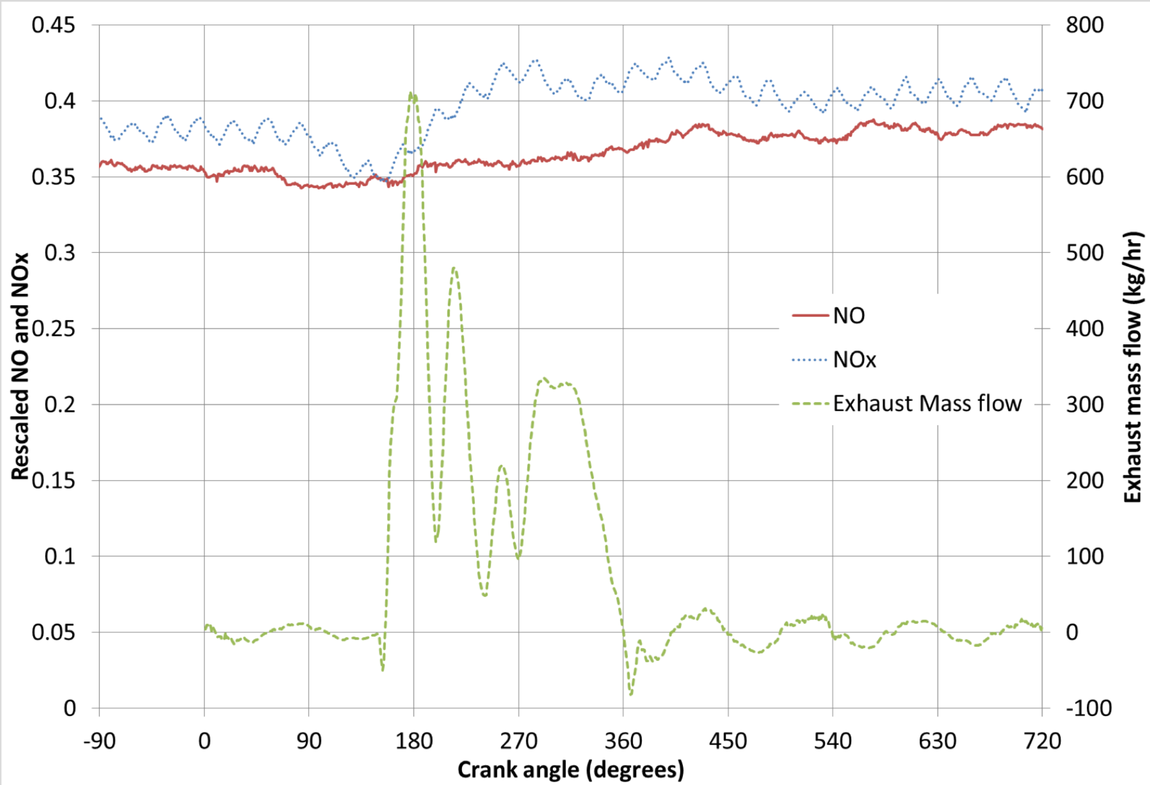
Results – crank angle resolved

- Happens at all engine conditions (here 1500 rpm / 6.9 bar, 32% EGR)
- Lower magnitudes with EGR (proportionally more NO_2)



Results – crank angle resolved

- A closer look at the slow NO rise rate in single cycle
- When exhaust MFR taken into account – slow rise rate has a large effect on cycle NO / NO_x ratio by mass



Discussion – Slow NO rise rate

- All instrumentation checked
- No fuel bound Nitrogen
- Slow NO rise rate ➔ more NO_2 near valves
- Why not every cycle?
- Nothing in literature
- Theory 1: cooled firedeck ➔ cooler gas near head ➔ earlier quenching of Zeldovich reactions ?
- Theory 2: Glarbog ➔ very fast NO_2 production until critical pressure
- Theory 3: Injector dribble ➔ HC promotes NO_2 production

Conclusions

- CA resolved NO and NO_x measurements
- Cyclic NO & NO_x well correlated ($R^2 > 0.95$) with P_{Max}
- P_{Max} ➔ T_{Max} ➔ NO & NO_x formation
- Changing NO_2 / NO_x ratio during exhaust
    - More NO_2 emitted during blowdown vs displacement
    - Not repeatable every cycle
    - Present at all operating points
    - Cooled fire-deck leading to spatial variation?
- Only observable with Fast NO_x instrument

Acknowledgements

- Co-authors
- Richard Stone
- Kendal Bushe

Thank you

- Leach FCP, Davy MH, Peckham MS, "Cycle-to-cycle NO & NO_x Emissions from a HSDI Diesel Engine". ASME Journal of Engineering for Gas Turbines and Power. 141(8), 081007, 2019, doi:10.1115/1.4043218

- Leach FCP, Davy MH, Peckham MS, "Cyclic NO_2:NO_x ratio from a diesel engine undergoing transient load steps". International Journal of Engine Research, 2019, doi:10.1177/1468087419833202

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